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Railgun Launcher Efficiency: Useful Measure or Misused Metric?

by Alexander E. Zielinski, James F. Newill, and Trevor Watt

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Railgun Launcher Efficiency: Useful Measure or Misused Metric?

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Abstract

The efficiency of an electromagnetic railgun is assessed. In addition to electrical and kinematic loss terms, the portion of useful mass launched downrange is considered. Both integrated and fixed integrated launch package design approaches are considered using a system assessment code. Various current profiles are used to assess the performance of the launcher and integrated launch-package performance for a 3.52-kg launch package at a muzzle velocity of 2.5 km/s in 6 m of travel. It is found that the majority of electrically efficient launchers do not provide the most useful payload. A few percent reduction in the most efficient launcher can provide up to 18% additional useful energy. Furthermore, the launcher designed in concert with the launch package was found to also increase the amount of useful energy by an additional 7%.

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1. Introduction

Launcher efficiency is defined as the ratio of the kinetic energy at muzzle exit to the electrical energy delivered to the breech. The breech energy can also be defined as the muzzle energy plus the sum of all the electrical and kinematic losses. In railgun experiments and simulations, the breech energy is simply the integral of the product of the breech voltage and current. The electrical-loss terms considered in this report are associated with the bulk-armature conductor, rail and armature interface, and the rails. The current profiles selected for this study assume that the rail current is zero at muzzle exit and therefore the stored inductive energy terms are zero. In reality, the current can be forced to zero either by pulsed power supply design [1, 2], or shunt devices (active [3] or passive [4, 5]), located at the muzzle of the launcher.

A medium-caliber hypervelocity shot (MCL122), which achieved a fairly high transition velocity, had a launcher efficiency of 40%, with a distribution of losses as follows: residual inductive 5%, rail resistive 35%, and armature losses 20% [6]. One of the most recent large-caliber firings had a launcher efficiency of 45% with a distribution of losses as follows: residual inductive 8%, friction 4%, rail resistive 17%, and armature losses 25% [7]. The smaller-rail loss in the large-caliber launcher is primarily due to the larger-rail conductor cross section. Clearly, ~60% of the breech energy was dissipated as heat for both cases. And, to that end, launcher efficiency very accurately depicts the electromechanical-conversion process. However, the medium-caliber test produced more useful energy (i.e., launch of a heavy metal subprojectile) than the referenced larger-caliber test.

If it were not for the nonlinear time and spatial dependence of the resistance of the rails, the distribution of energy could be easily calculated. Action, defined as the integral of the current squared over the acceleration time, is known from the mission requirements. Energy-loss terms are simply the product of the action and the resistance. The final velocity is constant for all the cases examined and, therefore, the kinematic losses (e.g., friction and air-compression) are nearly the same. Moreover, these losses amount to less than a few percent of the total losses.

The current profile effects the amount of rail losses. The system code EMLP [8], in addition to assessing launcher and armature requirements, contains an extensive routine to calculate the resistance and energy loss in the rails [9].

The type of armature can effect the energy distribution in the railgun. For example, use of a plasma armature will greatly reduce the efficiency of the launcher [7]. Similar trends, although not to the same extent, can also be seen with different types of solid armatures, including magnetic obturators, fiber brushes, and trailing-arm armatures. In this assessment, only trailing-arm armatures (or C-shaped armatures) are considered as they have routinely demonstrated operation with heavy-metal payloads at hypervelocity [6, 10, 11].

The subject of this technical report is to determine the efficiency of a railgun and assess to what extent the efficiency can be increased. The performance is for the current Phase 2 goals namely, 3.52 kg to 2.5 km/s in 6 m of travel.

2. Technical Issues

2.1. Current Profile. In order to assess efficiency as a function of the shape of the current pulse, it is convenient to bound the pulse shape in terms of the desired performance. The current profiles in this report are generalized as shown in Figure 1. For all cases, Ix is set to zero and the rise time (tr) is 500 μs, elucidated from inbore structural-dynamic considerations [12, 13, 14]. Two cases are derived—one in which the current after the rise time is constant, and the second in which the current is allowed to droop after attaining its peak value. An inductance gradient, somewhat lower than that calculated for a reference design [14] of 0.6 μH/m, is assumed. Figure 2 shows the parameter space for the flat-top profile. The values for time indicated on the abscissa are for the rail current to start its decay (to) and for projectile exit (tf). The commutation time (tc) is the difference between tf and to.

The data in Figure 2 indicates that for relatively small values of tc, peak currents slightly in excess of 3 MA can meet the design goals with a barrel as short as 4 m. To meet the

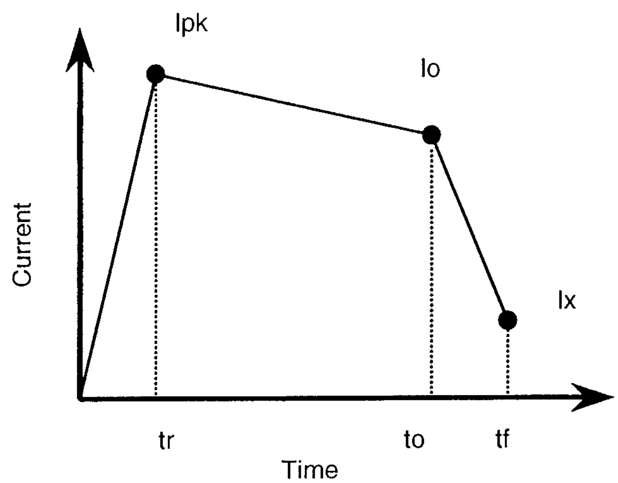

Figure 1. Generalized-Current Profile.

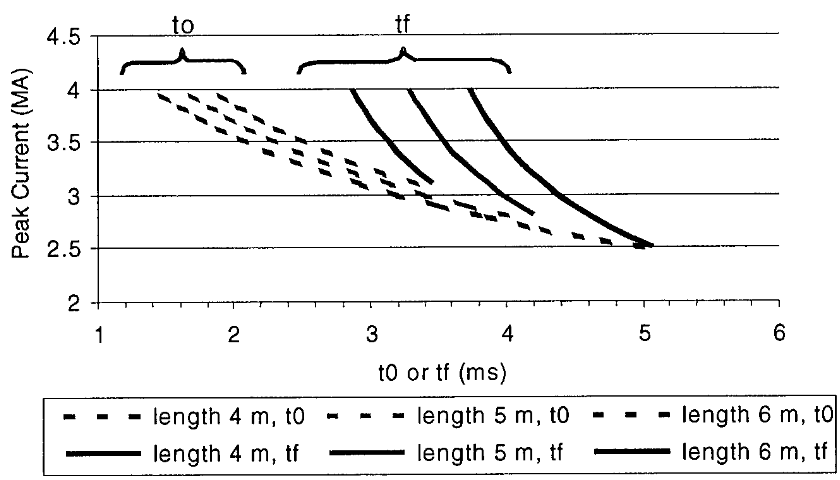

Figure 2. Parameters for Flat-Top-Current Pulse.

performance requirements (3.52 kg to 2.5 km/s in 6 m of travel), a peak current as low as 2.5 MA will suffice.

The second case, illustrated in Figure 3, shows the increase in current required for allowing the rail current to droop after attaining its maximum value. It is assumed that tc = tr = 500 μs.

Initially, four representative pulses were used as input to the EMLP code covering aspects of both the flat-top and drooping cases. The cursory analysis indicated that the most efficient

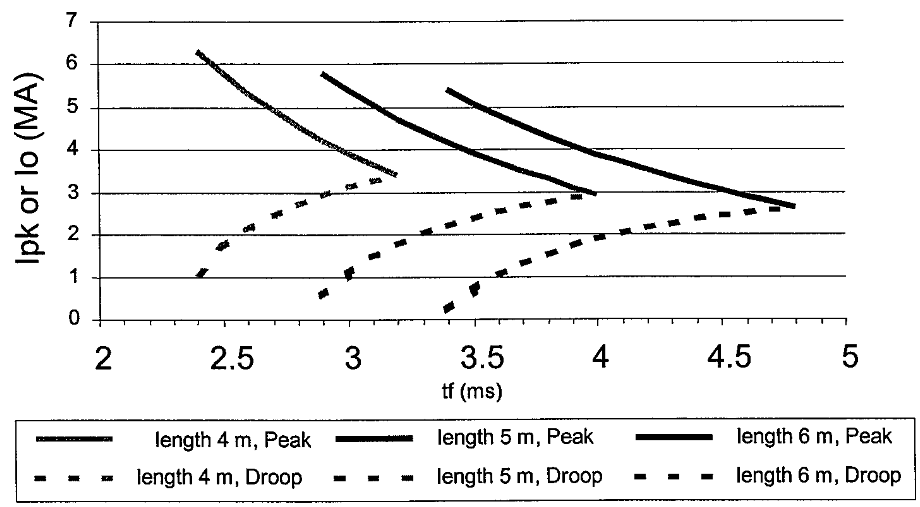

Figure 3. Parameters for a Drooping-Current Pulse.

launcher did not produce the most useful energy. The analysis also indicated that there was virtually no increase in efficiency for using a launcher less than 6 m in length. However, dynamic, vibratory, and cost issues may take precedence.

A more systemic approach was then used to quantify the dependence of performance with pulse profile. For this analysis, tr = tc and varied from 250 μs to 1,500 μs. It is assumed that the ILP and launcher system can tolerate the dynamic loads. A flat-top current pulse is also assumed. Additionally, while it is not unreasonable to expect the shape of the pulses illustrated in Figure 1, the time and current characteristics do place some burden on the pulsed power-system components (e.g., high voltage and high-time rate of change in current capacity). The current profiles under consideration have been addressed analytically for capacitor and rotating machine based supplies [1, 2]. Other pulse shapes are possible, but their analysis is beyond the rather simplistic representation illustrated in Figure 1. For the aforementioned time constraints, peak current increased accordingly from 2.6 MA to 3.2 MA in order to maintain the performance conditions at exit (3.52 kg at 2.5 km/s in 6 m). The ratio of the peak to average acceleration ranged from 1.1 for the 250 μs solutions to 1.7 for the 1,500 μs solutions.

Two cases are considered. In the first case, the code EMLP was used to design both the launcher and ILP (i.e., integrated approach). In the second case, the launcher was specified [15] and only the ILP was designed. The dimensions of the bore cross section for the specified launcher were calculated using a related system approach [15] and were relatively close to the dimensions generated for the various launchers using the EMLP code (66 × 126 mm).

A plot of the launcher performance, presented as both launcher efficiency and useful energy, is shown in Figure 4. The results are similar to the cursory analysis and indicate that the most efficient launcher does not produce the most useful energy. This result is because for the long rise and commutation times, a higher-peak current is needed to attain the same exit conditions. This profile produces a lower-average current during the acceleration, and hence, rail losses are somewhat reduced. On the other hand, a larger-peak current requires more armature structure to support the subprojectile loads. Hence, parasitic mass is increased.

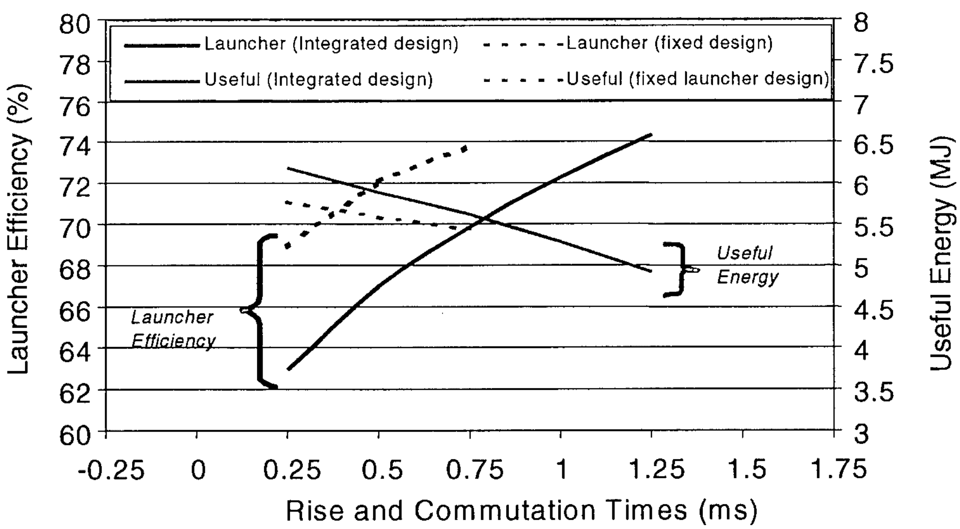

Figure 4. Launcher Performance.

The plot indicates that for a highly-integrated system, with considerations for short rise and commutation times, 6.2 MJ of useful energy can be delivered from the launcher. Specifying a launcher and designing the ILP to fit into the launcher, produces roughly 7% less useful energy (5.7 MJ). Additionally, if the rise and commutation times are rather long, roughly 4.9 MJ of useful energy is produced irrespective of the degree of integration. It should be noted that energy delivered to the breech is not held constant. For example, the 6.2 MJ solution requires 17.5 MJ, while the 5.4 MJ solution requires 15.8 MJ of delivered energy—nearly one half of the additional 1.7 MJ of breech energy appears as useful energy.

A pictorial representation of the ILP produced by both the integrated approach (6.2 MJ) and specified launcher approach (5.4 MJ) is shown in Figure 5.

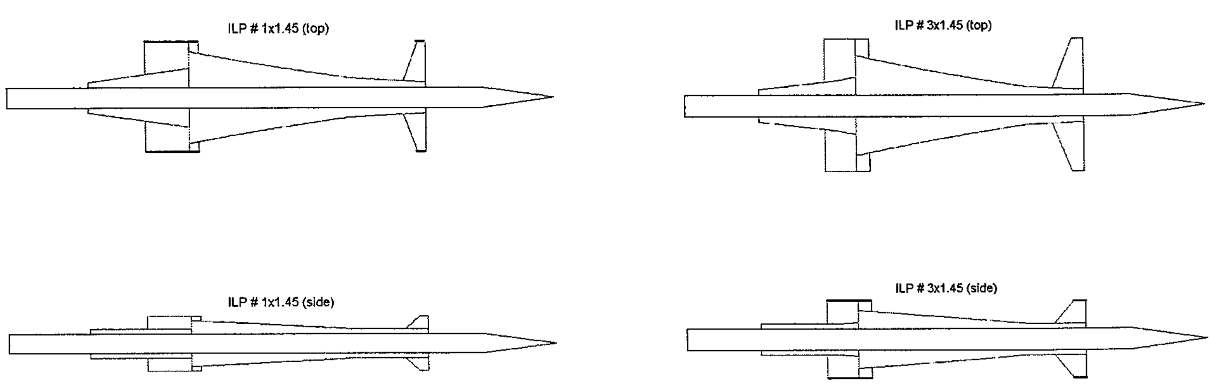

Figure 5. Illustration of 6.2 MJ (Left) and 5.4 MJ (Right) ILPs.

2.2. Muzzle-Shunt Considerations. The analysis in the proceeding section assumed that the launcher current at exit was zero. This result can be achieved if the frequency and switching of the pulsed-power supply are appropriately selected. In the event that voltage generation near the end of launch becomes untenable, a device located at the end of the muzzle (i.e., muzzle shunt) can be used to commutate the current from the armature to the circuit path containing the launcher and pulsed-power supply, thereby allowing any residual inductive energy to be transferred back to the system. Rail losses will be increased above those calculated for Figure 4 due to maintaining the flat-top current until projectile exit. For short commutation times, the additional increase in rail loss is expected to be small. Finally, the simulations only consider launcher performance and efficiency up to projectile exit. The process of energy recovery is highly dependent on details for the pulsed-power system and is not considered here.

The penalty for use of a muzzle-shunt device is the resistance inherent in the shunt. This section examines the extent of this loss in a passive muzzle-shunt device. The analysis presented is similar to one found in the literature [5]; however, a time-marching scheme is used and the voltage drop across the armature is taken from recent experimental tests for a solid armature, hypervelocity ILP [6].

In this analysis, the aforementioned exit conditions are used with a launcher having an inductance gradient (L') of 0.5 μH/m and another where L' is 0.6 μH/m. The flat-top profiles calculated from Figure 2 are used for illustration. Inductance and resistance values for the shunt (Ls and Rs) are varied until the ILP exits the launcher with zero current in the armature. A plot illustrating the bounds to achieve zero exit current for Ls and Rs is shown in Figure 6. Values for Ls and Rs are less than 240 nH and 1600 μΩ, respectively. Commutation times are also indicated and are near the values required for the current profiles discussed in the previous section. Additionally, a predominately inductive device tends to minimize the energy dissipated in the shunt. However, even with a predominately resistive device, energy loss is on the order of 0.5 MJ, roughly the same order of magnitude as the kinematic losses. The time to complete the transfer of energy to the pulsed power system is not assessed.

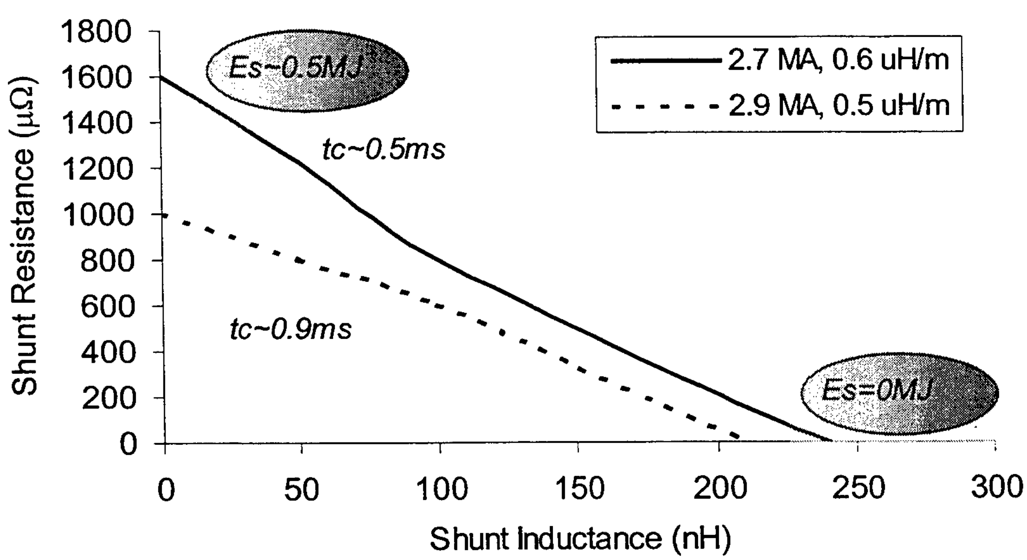

Figure 6. Muzzle-Shunt Parameter Space.

3. Issues and Conclusions

The efficiency of an electromagnetic railgun was assessed and found not to be the most useful metric. Rather, useful energy, determined from the launch velocity of the kinetic energy penetrator, is more beneficial. Furthermore, it is recommended that a highly integrated-design approach, considering the current profile delivered from the pulsed-power supply, launcher topology, and ILP payload can produce an efficient system yielding 6.2 MJ of useful energy.

A passive-muzzle shunt was analyzed and found to contribute marginally to the inefficiency of the launcher. Analysis was terminated at projectile exit and does not consider the details associated with energy recovery after projectile exit. The use of a muzzle shunt did, however, produce commutation times (~700 μs) on the same order as those required by a low-peak current solution (~2.7 MA). The alternative solution (i.e., no muzzle shunt) is not attractive considering efficiency, signature, and structural issues. There still remain ILP-based issues associated with rapid rise and commutation times. These issues must be balanced with pulse power and launcher requirements.

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